DEVELOPMENT OF HYBRID CEMENTITIOUS COMPOSITE (HCC) FOR SUSTAINABLE CONSTRUCTION IN SEA WATER ENVIRONMENT

ALONGE OLAYIWOLA RICHARD

UNIVERSITI SAINS MALAYSIA

2016

DEVELOPMENT OF HYBRID CEMENTITIOUS COMPOSITE (HCC) FOR SUSTAINABLE CONSTRUCTION IN SEA WATER ENVIRONMENT

by

ALONGE OLAYIWOLA RICHARD

Thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

MARCH 2016

DEDICATION

I dedicate this research study to the Almighty God, my wife and children, Oluwaseye Caroline Alonge, Esther Temiloluwa Alonge and Michael Oluwatimilehin Alonge, my late father, Mr. Isaac Oluwole Alonge and my mother, Mrs Victoria Alonge.

ACKNOWLEDGEMENT

First and foremost, my heartfelt gratitude is towards the Almighty God for endowing me with the grace, opportunity, support and spiritual backing to complete my PhD study.

I wish to express my sincere gratitude to my supervisor and adopted father, Professor, Dato' Dr.Mahyuddin B. Ramli for his unrelented efforts, conscious advice, guidance, encouragement, enthusiasm and constant financial support.

My appreciation goes to all the technical staffs of the School of Housing, Building and Plannings' structure and concrete laboratory, wood and metal laboratory. Likewise, all the support and help of all other administrative staffs of the School of HBP are noted and appreciated.

In the same vein, I wish to appreciate the Universiti Sains Malaysia (USM) management for the Postgraduate research grant (1000/PPBGN/846112) fund granted to me as well as the USM graduate assistance scheme award.

I will love to appreciate the entire pastorate, the management committee members, as well as all the members of Tabernacle of Grace Church, Penang, Malaysia.

My regards goes to all my co-PhD candidates in the research room of School HBP.

Finally, I appreciate my lovely wife and children, my mother and my siblings. Mrs. Oluwaseye Caroline, Esther Temiloluwa, Michael Oluwatimilehin, Madam Victoria Olutayo for their unflinching love, support and prayers coupled with their endurance during the journey of almost five years of my Master degree and PhD.

I say thanks to you all.

TABLES OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ACI	America Concrete Institute.
ASTM	America Society Testing Methods.
BF	Barchip Fibre
BSI	British Standards Institution
CF	Coconut Fibre
CNS	Colloids Nanosilica
ECC	Engineered Cementitious Composites
EDX	Energy Dispersion X-Ray
FRC	Fibre Reinforced Concrete
ITZ	Interfacial Transition Zone
MK	Metakaolin
OPC	Ordinary Portland Cement
OPFBF	Oil Palm Fruit Bunch Fibre
HCC	Hybrid Cementitious Composites
SEM	Scanning Electron Microscopy
SP	Superplasticizer

PEMBENTUKAN KOMPOSIT SIMEN HIBRID (HCC)

UNTUK PEMBINAAN LESTARI DI PERSEKITARAN AIR LAUT

ABSTRAK

Perbalahan utama dalam komuniti pembinaan ialah untuk menghasilkan konkrit bertetulang gentian (FRC) yang mempunyai ciri-ciri kejuruteraan yang baik serta keupayaan lenturan yang lebih tinggi. Metakaolin (MK) mempamerkan potensi yang sangat baik sebagai bahan bersimen tambahan (SCM) kerana tahap kereaktifan pozzolan yang tinggi serta pengurangan $Ca(OH)_2$ seawal satu hari untuk menghasilkan kekuatan awal. Demikian juga, ia menguatkan adunan campuran simen untuk menjalani proses pemadatan yang telah ditetapkan. Proses penerokaan eksperimen ini melibatkan penghasilan MK oleh makmal yang berasal daripada kaolin mentah dan pencirian MK dalam empat campuran adunan simen yang terdiri daripada simen, Coloids Nanosilica (CNS) dan Epoxy Resin. Komposisi kimia dan sifat fizikal MK telah dinilai menggunakan penganalisis laser partikel zarah, X-ray Fluorescence (XRF) dan X-ray Diffraction (XRD). Kajian ini menggunakan kriteria reka bentuk terhadap campuran konkrit berkomposit simen standard ECC M45 (dengan sedikit pengubahsuaian). Satu komposit simen hibrid (HCC) telah dihasilkan, didedahkan dalam persekitaran yang agresif iaitu dalam air laut dan air biasa untuk peringkat umur sehingga 365 hari. Sebanyak tujuh campuran termasuk kawalan telah direkabentuk dengan menggabungkan 10% MK, 1% CNS, 1% Epoxy Resin mengikut kiraan berat simen. Gentian barchip, serat kelapa dan serat buah kelapa sawit telah digabungkan pada 2% setiap satu mengikut sukatan berat pengikat. Penghibridan barchip dan setiap gentian semula jadi juga telah

digabungkan. Hasil kajian menunjukkan bahawa MK yang dihasilkan mempunyai alumina dan silika oksida yang lebih tinggi sebagai tambahan kepada penggredan halus terhadap saiz zarah. Penggabungan MK menyebabkan peningkatan dalam permintaan air untuk adunan dan masa set bagi keempat-empat adunan simen. MK, CNS dan Epoxy Resin meningkatkan sifat-sifat mekanikal pada awal usia dan sifat-sifat ketahanan HCC dengan penggabungan gentian hibrid. Di antara semua gentian, gentian barchip menunjukkan keputusan yang sangat memberangsangkan, manakala bagi hibrid barchip dan gentian kelapa gentian juga menunjukkan prestasi yang lebih baik berbanding barchip dan buah kelapa sawit. Sampel yang diawet di dalam air laut menunjukkan prestasi dan korelasi yang lebih baik daripada sampel yang diawet di dalam air. Panel-panel HCC dan rasuk yang direkabentuk telah mempamerkan ciri-ciri retak pertama yang lebih baik dan kekuatan lenturan yang lebih tinggi berbanding dengan kawalan. Walau bagaimanapun, panel gentian barchip dan rasuk menunjukkan prestasi yang lebih baik daripada yang lain.

DEVELOPMENT OF HYBRID CEMENTITIOUS COMPOSITE (HCC) FOR SUSTAINABLE CONSTRUCTION IN SEA WATER ENVIRONMENT

ABSTRACT

The major challenge in the construction community is to advance a new type of fibre reinforced concrete (FRC) which possesses favourable engineering features that yield a high flexural ability. Metakaolin (MK) display great potentials as a supplementary cementitious material (SCM) because of its high pozzolanic reactivity as well as reduction of $Ca(OH)_2$ as early as one day to produce early strength. Likewise, it intensifies the blended cement paste to undergo definite densification. The experimental exploration involves the laboratory production of MK from raw kaolin and characterization of MK quaternary blended cement mortar consists of cement, colloids nanosilica (CNS) and epoxy resin. The chemical compositions and physical properties of the MK were appraised using a laser particle size Analyzer, X-ray Fluorescence (XRF) and X-ray Diffraction (XRD). The study adopts the design criteria and mix proportion of engineered cementitious composites standard ECCM45 (with some modifications). A hybrid cementitious composite (HCC) was produced, exposed to both water and sea water for ages up to 365 days. A total of seven mixes including control were fabricated with the incorporation of 10% MK, 1% CNS, 1% of epoxy resin replacement of cement by weight. Barchip fibre, coconut and oil palm fruit bunch fibres were incorporated at 2% each by weight of binder. Hybridization of barchip and each of natural fibres were also incorporated. The results showed that the MK produced has higher alumina and silica oxides and very fine particle size grading. The incorporation of MK causes an increase in water demand of the mortar and the setting time of the quaternary cement mortar. The MK, CNS and epoxy resin enhance the early age mechanical properties and durability properties of the HCC even with the incorporation of the fibres and their hybridization. Among all the fibres, the barchip fibre generated very encouraging results while the hybridized barchip and coconut fibre likewise showed better performance over the samples of barchip and oil palm fruit bunch. The samples exposed in sea water revealed better performance and correlations of results than the samples exposed in water. The HCC panels and beams fabricated exhibited better first crack and ultimate flexural strength, multiple micro cracks width and crack spacing than the control. However, the barchip fibre panels and beam performed better than others.

CHAPTER ONE

INTRODUCTION

1.1 Introduction

This study focuses on the development of Metakaolin influence hybrid Cementitious Composite (HCC) made of natural materials. The main materials incorporated in the production of this natural HCC are Metakaolin, natural fibres, natural and localized fine sand, cement, nano silica and epoxy. This is done to take advantage of the abundance of natural materials to minimize cost, reduce energy expanded into the production of cement and other byproduct and also minimize environmental degradation hence contribute to the level of sustainability in the civil and construction industry.

This chapter of the thesis discusses the research study background, statement of the problem, the aim and objectives of the study, the significance of the research, the scope of the study and finally the layout of the thesis.

1.2 Background of the Research Study

The world is witnessing a high current of revolution in construction practices and materials production along with a new face of development. This is fuelled by rapid economic growth and a high rate of urbanization coupled with the issue of environmental management and sustainability (Suresh, 2004)..

In order to assist in the sustainable development challenges facing concrete industry, civil and construction industry, environmental friendly and sustainable concrete technology must be engaged including improved cement production process. This must also include the use of supplementary cementing materials, recycling concrete materials and other materials that can enhance the service life cycle of concrete structures. This will give credibility to the concrete and construction industry.

In tune with this realization and in accordance to the current technological advancements in the field of sustainable construction materials, various researches and studies have been carried out and still ongoing to meet up with the challenges. Lightweight concrete of various types was developed to control some of the shortcomings of traditional concrete, especially in the area of total mass and flexibilities, then the production of high performance and high strength concrete with the introduction of fibre and polymer materials in concrete (Nagaraj, et al., 1993, Naaman 2000, kearsley and Wainwright 2002, Gesoğlu, et al., 2004, Jones and McCarthy 2006, Kurama, et al., 2009, Bedoya-Ruiz, et al., 2010, Cheah and Ramli, 2012). In most of these new developments, additives, cementitious and pozzolans were used and fibres, wire mesh were equally engaged as reinforcement in many of the newly innovated concrete.

These rapid developments of innovative reinforced concrete support the development of fibre reinforced concrete, Ferrocement mortar and concrete and newly adopted Engineered Cementitious Composites. Fibre reinforced concrete, FRC, is made primarily of hydraulic cements, aggregates, water and discrete reinforcing fibres. It was developed with the view that the inclusion of fibres in concrete, mortar and cement paste can bring about improved engineering properties of the materials, such properties includes, flexural strength, fracture toughness, impact, thermal shock, resistance to fatigue and spalling, (Balaguru and Shah 1992, Nataraja, et al., 2005, Aruntaş, et al., 2008).

In the last decade, the technology of concrete has been experiencing fast development. Many endeavour to alter the unique, all known brittle performance of conventional plain concrete materials like cement paste or mortars and concrete has brought about a contemporary notion of high performance fibre reinforced cementitious composites (HPFRCCs) which showcase a special ductile behaviour. Hence, guarantee to be useful in various ranges of civil, building and infrastructure construction and applications as sum up by Concrete Institute in Japan (Naaman, 2003) and (Kunieda and Rokugo 2006). One out of many areas of practical application of this class of fibre reinforced cementitious composites material is the retrofitting, repairs and strengthening of concrete infrastructure and civil/ building structures.

Contemporary techniques of placing large amounts of fibres between 5-20% by volume into bulk structures such as columns, beams and connections have been successfully introduced. Some examples of this are SIFCON which has between 5-20% steel fibres and slurry infiltrated (Schneider 1992, Brandt 2008), SIMCON, of which 6% steel fibre mat was employed and slurry infiltrated (Li, et al., 2002, Habel, et al. 2006); slurry infiltrated steel wool and Compact reinforced concrete, CRC, matrix which has a volume contents of 5-10% fine steel fibres (Guerrini, 2000).

These materials have excellent mechanical properties coupled with strength properties improvement, fracture toughness and sometimes even appear to exhibit strain-hardening behaviour as in some thin-sheet FRCs. They also share primary importance with the main reinforcement in certain structural members as a result of their exhibited features. For instance, they have been considered for providing structural ductility in over-reinforced beams and likewise in brittle carbon FRP R/C structures (Naaman, 2003).

Furthermore, the quest for revolutionary building and civil engineering material that meets the standard structural strength and durability challenges without compromising sustainability features brought about the evolution of Engineered Cementitious Composite materials (ECC).

Engineered Cementitious Composites (ECC) is a type of high performance fibre- reinforced cementitious composite material that is characterized by a strain capacity of more than 3%, hence acts more like a ductile metal rather than like a brittle glass. It is a bendable concrete composed of all the ingredients of a traditional concrete with the exception of coarse aggregates or crushed stones and it is reinforced with micromechanically design polymer fibres. Micromechanically, in the sense that the mechanical interactions between ECC's fibre and matrix are described by a micromechanical model, which takes into account material properties and helps predict properties and guide ECC development. It has been optimized through the use of micromechanics in order to attain high ductility and tight micro-crack width even with moderate use of fibre contents, (Li, 2003, Wang, 2006). The volume content of fibre is 2% of short discontinuous fibres differs from what was used in FRC.

ECC incorporates super fine (100 microns in diameter) silica sand and tiny Polyvinyl Alcohol-fibres cover with a very thin, slick coating. This slick coating of the surface allows the fibre to begin slipping when they are overloaded so they are not subjected to fracturing and prevent the fibre from rupturing which could lead to large cracking in the components. According to micromechanics theory, ECC is tailored by fibre geometry interface properties and matrix toughness (Abdeen and Hodhod, 2010).

The Engineered Cementitious composite has 500 times more resistant to cracking and 40% lighter in weight compared to normal concrete. It is generally designed for maximum flexibility. And comparison studies result made available by School of Natural Resources and Environment’s Center for Sustainable Systems, in conjunction with the University of Michigan’s research group, reveals that over 60 years of service on a bridge deck, the ECC is 37% less expensive, consumes 40% less energy, and produces 39% less carbon dioxide (a major cause of global warming) than regular concrete.

ECC is a crack self- healing material, hence the crack damage recovers any stiffness lost when the material is damaged. The average crack width in ECC concrete is below 60 micrometers and that was considered to be about half the width of a human hair. Extra dry cement in the concrete exposed on the crack surfaces can react with water and carbon dioxide in air to heal and form a thin white scar of calcium carbonate (Li, 2003, Qian, et al., 2009, Kan and Shi, 2012). The application of this material is finding its way into precast plants, construction sites, and repair and retrofits jobs.

The most fundamental differences in the area of mechanical property between ECC and FRC is that while ECC is strain-harden, FRC is tension-softens after first cracking. In FRC, the first crack continues to open up as the fibres are ruptured or pull out and the stress-carrying capacity decreases. This post-peak tension-softening deformation is often represented by a softening stress-crack opening relationship. While, in ECC, a rising stress accompanies by increasing strain followed up the first crack. This strain-hardening response of ECC replaces the well known FRC tension-softening response only after several percent of straining has been attained, thus achieving a stress-strain curve with a shape similar to that of a ductile metal material. In addition to these, the material is considered to be extremely damaging tolerant and remains ductile even in severe shear loading conditions, (Lim and Li, 1997, Li, et al., 2002, Shang, 2006).

Fibres are made up of thread or filament formed from vegetable tissue, mineral substances or textile materials. Fibres can be employed in self compacting concrete, natural or artificial lightweight aggregate concrete and expanded polystyrene concrete (Corinaldesi and Moriconi, 2004, Düzgün, et al., 2005). The current technological development in term of various types of fibre has led to the creation of more new opportunities for the improvement of fibre reinforced cementitious composite materials. Most often the strategy employed in the materials design is targeted at composites design with improved tensile response. This is by taking advantage of the effectiveness of combined contribution of various types of fibres to the comprehensive tensile response of the composites. The usage of fibres of different features and natures is combined with distinct features and geometrical and material properties in such a composite as hybrid fibre reinforced cementitious composites have been studied and reported in literatures to improve the material properties of many fibre reinforced cementitious composites (Lawler, et al., 2003, Banthia and Gupta, 2004, Ahmad, et al. 2007). Generally, studies shows that the most important benefit derived from the appropriation of hybrid fibre reinforcement techniques in the fibre reinforced cementitious composites is the potentials to constrain or confine cracking at different scales of the cracking process (Ahmed, et al., 2007). Likewise, it was confirmed that micro fibre improves the pull out the response of macro fibre as well, hence produce high strength composites (Ahmed and Maalej, 2009). This dictates the utilization of hybrid fibre in this study.

However, with the new innovated ECC, it is somehow revealed that composite material properties depend on three groups of constituent properties, namely; the fibre, matrix and the interface properties. Composite optimization requires that the combined influence of all relevant parameters on composite properties be known and this can lead to a good composite material with excellent performance and contain only a moderate fibre volume fraction. Hence, the desire to study a hybrid cementitious composite was produced based on ECC design and with natural features.

The advent of this composite material has led to many research studies with various focuses on the mechanical properties, durability, micromechanics properties and many others. Most of these based their matrix design on mono-fibre and hybrid fibre. A handful research knowledge is known about the properties and durability of sustainable hybrid fibre reinforced ECC made of natural cementitious materials and fibres.

Supplementary cementitious materials (SCM) are considered to be finely ground solid materials that are engaged for cement replacement partially, in a concrete mixture. This class of materials reacts with hydrating cement chemically to produce a modified microstructure paste. SCM may either possess pozzolanic or latent hydraulic reactivity but in some instances it may possess both. Pozzolans are finely silicious material which can react chemically with cements' calcium hydroxide (CH), in the presence of water to produce a cementitious compound. The origin of pozzolans can either be natural or industrial. Volcanic ash, diatomaceous earth and kaolin are few examples of natural pozzolans while, fly ash, which is the most extensively used SCM, Silica fumes, granulated blast furnace slag are few examples of industrial waste pozzolans.

Metakaolin (MK) is a type of SCM that is unique in nature in the sense that it is not entirely natural and not a by-product of an industrial process, it is extracted from a naturally occurring mineral and it is manufactured explicitly for cementing application purposes. It is an SCM that conforms to ASTM C 618, class N pozzolan specification. MK is procured through the process of calcinations of kaolinitic clays over a certain period of time at a specific temperature range. It is a pozzolanic material which, when added to lime mortar mixes can result in improved mechanical properties.

In this modern age, MK, based on its high pozzolanic properties and its' high surface area, coupled with its amorphous structure has been used as an effective and highly active pozzolan for partial cement replacement in concrete and concrete mortar (Frías and Cabrera, 2000, Asbridge et al., 2002). Studies by various researchers has shown the capability of MK has been used as a cementitious material and additive to improve both the durabilities and mechanical properties of concrete and concrete mortar (Fraire-Luna, et al., 2006, Kim, et al., 2007, Janotka, et al., 2010). Likewise, in the production of high strength concrete Yu, et al., (2010) and high – ultra high performance concrete (Vejmelkova, et al., 2010). Despite the cost factor which is not favourable to the use of MK, there are potentials of the high utilization of the pozzolans due to the fact that there is a current shortage of mineral admixture such as high quality slag and silica fumes. Even fly ash, which is most generally used mineral admixtures will soon fade away with the invention of the biomass fuel production. Hence, the need for naturally available cementitious material.

Nanotechnology is currently considered as one of the twenty – first century's key technology Gammampila, et al., (2010), its economic importance is sharply on the rise. The meaning of Nanotechnology varies from one field to the other and also it varies based on country to country. Nanotechnology is commonly defined as the understanding, control, and restricting of matter in the order of nanometers (i.e., less than 100 nm) to create materials with fundamentally new properties and functions (Roco, 2007, Roco, 2011). Concrete, which is most pervasive material for construction in the world is a nanostructured material with multiple phase and composite that wears over a period of time, (Sanchez and Sobolev, 2010). It consists of an amorphous phase, which are in nanometre to micrometer crystal size and bound with water. It has properties that exist in multiple length scales, i.e. from nano to micro and micro to macro. Hence, concrete nanoengineering can take place in one or more of the highlighted three phases such as solid phases, liquid phases and interfaces between liquid and solid or solid to solid (Garboczi, 2009).

Concrete material mechanical behaviour depends to some great extent on the structural elements and exceptional that are active on micro and nanoscale as the size of the calcium silicate hydrate (C-S-H) phase falls within few nanometers. This eventually has an indicative effect on the concrete performance as the structure is more sensitive to movement of moisture content hence shrinkage and cracking consequently when there are constraints in elements sizes (Jennings, et al., 2007). Therefore, nanoparticle, such as nanosilica (powdery and colloidal types), may have potential to manipulate concrete with superior properties by means of optimization of material behaviour and performance necessary for significant enhancement of concrete mechanical, durability and sustainability performance. This determines the use of nanosilica in this study to enhance the performance of HCC.

1.3 Statement of Problem

In contemporary human dispensation, concrete is the most accepted widely used construction material with estimated annual consumption of approximately ten billion metric tonnes (Yaprak, et al., 2011). Ordinary Portland cement is the main components of concrete, that is, the major binder agent. But study shows that the production of cement accounted for 5% of the global anthropogenic carbon dioxide emission. The main source of carbon dioxide emission is from the calcinations process of limestones and combustion of fuel in the kiln. Recently, the cement industry through the production of cement, is ranked third highest in world energy consumption, which contributes up to 19.7 % of the whole global industrial energy consumption as stipulated by (Kolip and Savas, 2010). Literature also confirmed that for every tonne of ordinary Portland cement produced, an approximate of 222 kg of carbon dioxide are emitted and discharged into the atmospheric air, this resulted into a serious environmental problem (Worrell, et al., 2001, Boden, et al., 2009).

The contemporary normal concrete is considered to be very sensitive to crack formation and as the cracks grow wide, the more the endanger of the durability of such concrete hence the need for repair. But this repair works always raises the life-cycle cost of the concrete as it involves intense labour works and as the structure become redundant during the period of damages and in the course of repairs (Van and De Belie, 2013).

Plain concrete consists of a very low tensile strength, very low ductility and little measures of crack resistance. It contains inherent internal micro-cracks which are due to drying shrinkage and the propagation of these cracks occurs because of its poor tensile strength, all these combine, eventually leads to brittle failure of the concrete. In the same vein, infrastructures can as well experience a wide range of dynamic loads, severe structural failure and eventual damage even catastrophic failures have occurred in some extreme cases, hence Yang and Li, (2012) suggested that there is a need to design civil infrastructure that are resilient to seismic, impact, and dynamic loading to enhance public safety.

A remarkable advanced development of high performance cementitious materials (HPC) has taken place in the past years. This includes high strength concretes with low water to binder ratio, high performance fibre reinforced cementitious composites (HPFRC) which exhibit improved strength and ductility, green concrete, which are more environmental friendly and contain increase contents of by-products and mineral admixtures. It makes use of different mineral admixtures to partially replace cement (Zhongwei, 1998, Chen and Liu, 2008). The most widely available and mostly used admixtures are silica fume (SF), fly ash (FA) and ground granulated blast furnace slag (GGBS). But despite all the favourable properties and high performance attributes to these composites, their wider applications are highly hindered by their special processing requirement due to high fibre volume fractions and they are often restricted to precast members, hence costly. In furtherance of this, a major challenge to the research community is to develop a unique new class of FRC that possesses some outstanding features of all various classes of FRC's that are in use today. The features should include, among others, flexible processing, and short fibres of moderate volume fractions, isotropic properties and high performances as a structural member. This led to the study of the flexural property of HCC.

Nonetheless, in order to achieve better strain capacity and multiple cracking, restriction is made for the use of only fine sand in ECC (Zhang and Leng, 2008), this however, resulted to the elimination of coarse aggregates hence the higher cement content compared to conventional structural concrete. A typical ECC cement content can be as high as 1000 kg/m^3. Each tonne of cement produced emits an equal tonne of carbon dioxide, which is responsible for five percent (5%) global green house gas emission (Van Oss and Padovani, 2002). Consequently, reasoning from global sustainable development, it is crucial to advance a sustainable, natural material contained in ECC by incorporating naturally derived mineral admixture to partially replace cement in concrete materials.

In line with this is the use of fly ash in the ECC. Recent studies revealed that fly ash has been an essential content of ECC, to improve the engineering properties most especially, the mechanical properties and as well reduce drying shrinkage of ECC (Yang, et al., 2007, Zhu, et al., 2009, Zhu, et al., 2010) an alternative, sustainable material must be sought. Be that as it may, the lower strength in the early age hinders the application of ECC material in some application whereby early strength is the main focus.

The commonly used fibre in ECCs is Polyvinyl alcohol fibre (PVA), it is considered the most suitable polymeric fibres to be used as reinforcement. This is despite its deficiencies which has to do with its' microstructure characteristics and hydrophilic nature. This makes it to have a tendency to rupture instead of being pulled out, hence, poses challenges to material design, (Wang and Li, 2005). Also, the interfacial bond strength of PVA fibre in ECC was said to be excessive because of its' hydrophilic nature and this was suggested to be artificially lowered by the application of surface coating agents (Victor, 2002). This is apart from the demerits such as high cost, quality balance to the highly cost sensitive construction sector and the scarcity of the fibre in some developing countries. Also, the current version of ECC clearly outperforms concrete in terms of mechanical properties yet its production has greater environmental burdens than concrete due to the high cement content and the inclusion of polymeric fibres, (Li, et al., 2004) Moreso, the bond properties of PVA fibre without any treatment are far above the optimal values which is currently established to be between the ranges of 1.5 – 2.5 N/mm^2, Wang and Li, 2005).

Above all, the design of ECC M45 which form the basis of ECC design, has been performed based on the micro-mechanical design theory constraining the alteration of ingredients' type and amount. Water-binder ratio, fibre and sand-binder ratio can be considered as mixture constraints of ECC design, (Şahmaran, et al., 2012).

All these stipulated points mentioned above brings about the agitation for the development of HCC for sustainable construction.

1.4 Aim and Objectives

This research is aimed towards the investigation of flexural resistance of hybrid cementitious composites (HCC) developed for sustainable construction most importantly in a marine or aggressive environment. This will embrace among others the production of MK in the laboratory and the optimization of composite materials including natural and synthetic fibre, analysing the features and structures, including mechanical, engineering and durability properties of the develop sandwich composite materials.

To achieve this aim, the following objectives are set;

1. To produce MK and study the particle morphology, chemical compositions, mineralogy, particle size distribution, specific gravity, rheology and engineering properties of the HCC.

2. To investigate the influence of the incorporation of MK as partial cement replacement on the HCC's durability properties.
3. To study the effect of both sea water and water environment on the engineering properties and performance of HCC.
4. To investigate the flexural property of the produced HCC structural panels and beam.

1.5 Research significance

Considering the numerous kaolin mines in local areas around the world, this research study is executed to gather experimental information on the physical and chemical properties of MK produced from natural kaolin clay in the laboratory. It also touches on the investigation of the flexural performance of HCC mixtures that contain laboratory produced MK. The rheological, mechanical, durability properties and characteristics of the HCC were also studied. This is to justify the use of MK as a supplementary binder material in the HCC.

Focusing on mechanical properties, the concepts of introducing discontinuous hybrid fibres which include local natural fibres and synthetic fibres in HCC to provide the needed pseudo strained flexural strain is scarce hence the bridging of the knowledge gap through this study.

In addition, contemporary construction practices in relation to reinforced concrete or concrete materials such as HCC have been in need of high performance, low cost and durable type of materials. The two main criteria of high performance concrete always sought to include high strength and an improved durability. Since shrinkage and permeability are directly related to the durability of the concrete, the improvement, realization and rehabilitation of these features through the use of some high reactivity mineral admixture such as MK comes into preeminent.

Hence, the research study is designed with the main focus of bridging these knowledge gaps and supply specific conclusive results. An effort was made to improve the ductility performance and deflection capacity of a structural beam by the incorporation of steel reinforcement with hybrid natural and synthetic fibres.

Experimental data on flexural response, crack patterns, ductility and mechanical behaviour collected from the testing of the structural panels and beams made of sustainable HCC will definitely contribute towards a better understanding of the responses to structural load, ductility capacity, load compressive strain behaviour, service load capacity, cracking behaviour, failure mode and serviceability property upon being subjected to various degrees of load capacity. This in turn can be used for the prediction of both mechanical and engineering behaviour of a structural beam in infrastructure, civil and building engineering industry.

1.6 Scope of work

The centre focus of this research includes the following;

1. The production of MK from refined kaolin clay and the characterization of the binder materials.

2. The study of the rheological, engineering properties of HCC with the incorporation of MK.
3. Investigating the influence of MK incorporation into HCC, as a partial cement replacement, on durability properties.
4. Study the effect of sea water and ordinary water environment on the engineering properties and the performance capacity of the HCC.
5. Lastly, an assessment of the structural and flexural responses of structural beam panels in relation to load response, load compressive strain, ultimate load capacity, cracks development characteristics and failure modes.

The production of MK includes the process of calcination of kaolin clay using the small laboratory oven, then the chemical property assessment which includes evaluation of chemical composition, the mineral phases and loss on ignition of MK. The physical property assessment includes particle size grading determination, determination of specific gravity of MK and OPC.

The evaluation of the properties of MK blended cement, as well as MK- CNS and epoxy blended cement containing 10% of MK, 1% of CNS and 1% of epoxy with the remain percentage of binder content as cement.

Rheological study of the HCC includes a slump test and the flow value of the mixes in the fresh state. Meanwhile, the mechanical properties include, among others, the determination of characteristics compressive strength and flexural strength at various ages of samples. Velocity of pulse propagation through the hardened HCC mix is also investigated to study the quality of hardened HCC. The dynamic and static modulus of elasticity of the hardened HCC was investigated for the assessment of stiffness features.

The durability properties study includes water absorption determination, air permeability properties of the hardened HCC, rates of carbonation and chloride diffusion. All these are determined to investigate the resistance to environmental aggressive agents. Since, it is a general assumption that durability are closely related to porosity and micro pore structure, the total porosity test is conducted on the hardened HCC with the inclusion of Scanning Electron Microscopy investigation to picture the micro-pore structure of the HCC.

The dimensional durability of high strength HCC includes the measurement of the changes in length via drying shrinkage. This is measured up till 365 days from the day of casting and drying exposure.

The assessment of structural behaviour is carried out on reinforced HCC beams with dimensions 1300 x 300 x 225 mm. The assessment parameter includes flexural and load-deflection response, bending load, service load capacity, the ultimate load capacity, and failure mode and crack development behaviour.

Hence, the limitation of this research study is as stated hereafter;

1. The maximum content of MK used in this experiment mixes is 10%, while, CNS and epoxy content is 1% each of the total binder.
2. This study does not consider the air exposure system as only sea water and portable water are considered.

3. The exposure period in the study is limited to 365 days and other days after this was not considered.

1.7 The thesis Layout

This thesis consists of seven chapters that covers the introduction and the investigations on the engineering and durability properties of HCC.

The chapter One includes the background of the study where the details of the research were summarized laying emphasis on the developmental stages of sustainable fibre reinforced concrete and HPFRCC composites reinforced with discontinuous or discrete fibres which include the development of ECC. It also includes the scope of the study, major aim and objectives, the benefit of the research and concluded with the scope and limitation of the study.

In Chapter Two, detailed critical review of related literatures on ECC and MK and colloidal nanosilica (CNS) as a supplementary binder in concrete composites is presented. The physical and chemical properties of MK as natural additives and substitute of binding material are highlighted. The design criteria, mix proportion and the properties of ECC M45 are presented likewise. The influence of MK inclusion on the eventual mechanical strength of concrete and concrete materials as well as on both fibre and hybrid ECC, concrete and mortar, most importantly the compressive and flexural strength properties at early ages and prolonged ages of exposure under different exposure condition is discussed and reviewed.

The centre focus of chapter Three is the detailed report of the experimental programme and the appropriate test methodology. Apart from this, the substantial criterion of examination or exploration programme are explained.

Chapter Four detailed the rheological properties of MK blended cement paste namely standard consistency, initial and final setting time of paste, flow and slump test of fresh composite paste. Detailed explanation of the non-destructive and destructive examination, which involve ultrasonic pulse velocity using hardened sample, static and dynamic modulus of elasticity, compressive strength and flexural strength of the hardened HCC samples. Aside this, an all inclusive discourse on the drying shrinkage property of the HCC sample is analysed in this chapter.

A detailed assessment on water absorption, rate of carbonation, intrinsic air permeability and chloride permeability are presented in Chapter Five and all these are in the examination of the durability property of the HCC. In this chapter, total porosity and Scanning Electron Micrographs are presented for additional evidences to justify the durability properties of the study samples.

The Chapter six of the thesis emphasis on the structural behaviour of HCC beam subjected to a varying flexural load degree to the very ultimate failure of the sandwich composites. Details are also given on analytical method of approach for the prediction of serviceability moment capacity, the ultimate load capacity, crack width and crack spacings.

The last chapter, which is the Seventh chapter gives the comprehensive conclusion reports from the experimental works in summary. It also includes the recommendations for implementation and future research opportunities.

CHAPTER TWO

LITERATURE REVIEW

2.1 General Appraisal

This chapter contains a critical look at the past literatures on the integral elements of this research study. For a research study to be worthy, a constructive critical review of past research works of the notable professionals and researchers needs to be evaluated and reviewed. This chapter shall highlight the new technological inventions in relation to engineered cementitious composite, natural additives, kaolin and metakaolin. Likewise, it gives details of nanotechnology and their applications in concrete, natural and artificial fibres. The review shall also touch on their historical background and changes in the use of these materials over time.

A general overview of sea water and portable water exposure was done. The penetration effect and consequences of both sea water and portable water was reviewed, such effects as chloride ions, sulphate and salt crystallization. The later part of this chapter shall be the summary of the literature review.

2.2 Historic issues about Kaolin

Kaolin is one of the most abundant natural minerals in the world. It is a fine, white clay that has been used in the manufacture of porcelain and paper coating traditionally. Fundamentally, the term kaolin is derived from the name of the Chinese town known as Kao-ling, which is translated loosely as 'High ridge'. This town is home to the mountain that yielded the first kaolin that was sent to Europe. It is from this that MK is obtained.

The first ever use of MK as contain in record was in 1962, when it was incorporated in concrete mix in Jupia Dam located in Brazil. Kaolin has been available in commercial quantity in most countries of the world since mid-1990s. It is usually white or nearly white in colour and not lined and consists of the mineral kaolinite with slight content of quartz, mica and feldspar derived majorly through the weathering process. There are different grades of kaolin, it includes premium grade which is used majorly as coating agent and ceramic manufacturing like high quality dishes, porcelain and some electrical insulation. The regular grade of kaolin is suitable for use in fillers and paper, paints etc.

Kaolin physical and chemical characteristics regulate its eventual application. Although it is concluded through studies that some of these physical and chemical features are usually hinged on the immediate environment of deposition, geological origin, method of processing, and geographic source (Murray and Kogel 2005). In some instances, the presence of impurities, mainly iron oxide and hydroxide and titanium- bearing materials diminish the kaolin quality and affects its usefulness for different type of application, industrial or commercial purposes. Few of the properties of kaolin are highlighted in Table 2.1.

Table 2.1 Properties of kaolin (Prasad, et al.,1991)

Properties	**Description**
Color	Usually white, colourless, greenish or yellow
Luster	Earthy
Transparency	Crystals are translucent
Cleavage	Perfect in one direction,basal
Fracture	Earthy
Hardness	1.5-2 (can leave marks on paper)
Specific gravity	2.6 (average)

Kaolin formation has a significant effect on its industrial applications. For instance, sedimentary kaolin has a higher economic value compared to primary kaolin (Hadi, 2008).

The major constituent of kaolinite are a hydrous aluminium silicate with an approximate compound composed of $2H_2O.\ Al_2O_3.2SiO_2$. Kaolinite is regarded as the clay minerals, which produce the plasticity features of the raw material and at the same time change properties during the heating process to produce another more beneficial material. In structural view, the kaolinite consists of alumina octahedral sheets and also silica tetrahedral sheets, well starched interspersely with the theoretical composition of SiO_2 which is 46%, Al_2O_3 is 39.5%, and H_2O is 13.96%. The crystal of kaolinite is pseudo-hexagonal along with plates, few larger books and stacks of vermicular (Murray, 2000). Kaolin has particle sizes which range from 0.2 to 15 µm with 10,000-29,000 m^2/kg specific area.

According to studies, Kaolin is considered as one of the most widely used industrial minerals, its' total output in the world is estimated to be 25 million tonnes and above (Nkoumbou, et al., 2009). Its deposit is found in many parts of the world with United State of America and Uzbekistan having the largest formation of kaolin. Figure 2.1 shows the colour of kaolin. It is largely used in different industrial